Chaos, Solitons & Fractals 68 (2014) 151–158

Contents lists available at ScienceDirect

Chaos, Solitons & Fractals

Nonlinear Science, and Nonequilibrium and Complex Phenomena

journal homepage: www.elsevier.com/locate/chaos

Two time-delay dynamic model on the transmission of malicious signals in wireless sensor network

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ARTICLE INFO

Article history:
Received 5 June 2014
Accepted 11 August 2014
Available online 7 September 2014

ABSTRACT

Deployed in a hostile environment, motes of a Wireless sensor network (WSN) could be easily compromised by the attackers because of several constraints such as limited processing capabilities, memory space, and limited battery life time etc. While transmitting the data to their neighbour motes within the network, motes are easily compromised due to resource constraints. Here time delay can play an efficient role to reduce the adversary effect on motes. In this paper, we propose an epidemic model SEIR (Susceptible–Exposed–Infectious–Recovered) with two time delays to describe the transmission dynamics of malicious signals in wireless sensor network. The first delay accounts for an exposed (latent) period while the second delay is for the temporary immunity period due to multiple worm outbreaks. The dynamical behaviour of worm-free equilibrium and endemic equilibrium is shown from the point of stability which switches under some threshold condition specified by the basic reproduction number. Our results show that the global properties of equilibria also depends on the threshold condition and that latent and temporary immunity period in a mote does not affect the stability, but they play a positive role to control malicious attack. Moreover, numerical simulations are given to support the theoretical analysis.

1. Introduction

In recent years, with the rapid development of various network applications, Internet has become powerful mechanism for propagation of malicious signals in the network. Among the various network, wireless sensor network (WSN) is one of the most vulnerable to attack of malicious signals because nodes are often placed in a hostile or dangerous environment where they are not physically safe and also due to limited processing capabilities, memory and limited power source motes change their communicating behaviour. Many models have been proposed to predict the propagation of worms in WSN, and some worms prevention strategies have also been taken into consideration. Previous work on worm modelling neglect the impact of multiple worm outbreaks on network [1–3]. New network worms are being created in major scale these days, whereas, the strains of old worms continue to circulate around the internet. Many models have considered static or permanent immunization where a mote is permanently immunized but in reality, immunization must be taken as temporary because of multiple worm outbreaks since a mote being recovered from a certain worm can be again reinfected by other worms immediately [1–3]. Thus, in order to represent the actual dynamics of spreading behaviour of epidemic and to predict future outbreaks, it is natural to include the effect of immunity into the mathematical models. On adequate interconnection between a susceptible and an infective mote, a susceptible mote becomes exposed, that is, infected but not infective. The mote while collecting the data from the network becomes

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http://dx.doi.org/10.1016/j.chaos.2014.08.006
0960-0779/

infected but due to low energy efficiency because of attack of malware it does not have the capability to transmit the malicious data to their neighbour motes. These types of motes remain in the exposed class for a certain latent period before becoming infective. Our main aim is to study the behaviour of epidemics, that is, analysis of different states of the model, and their stability and also to study the significant role of time delay in model. By incorporating temporary immunity period and latent period in WSN model we try to know the effect of delay in different states of the model. Generally, an epidemic model contains two equilibria: one worm-free-equilibrium and the other endemic equilibrium. The stability of a worm-free-equilibrium as well as the existence of other non trivial equilibria can be determined by using some threshold condition given by the basic reproduction ratio, which quantifies that how many secondary infections appear from a single infected mote put in the collection of susceptible motes. Inclusion of time delays means that the model can be formulated as functional differential equations. In our paper, time delay is introduced in worm propagation model with temporary immunization, the stability of which is analysed. Through analysis, it is found that the introduction of time delay decreases the possibilities of worm propagation in WSN. Too large time delay may lead to large number of infected motes, because of which worm propagation persists in the system. This paper thus focuses on the effect of time delay on WSN with worm propagation.

The structure of this paper is as follows. In section 2, related work on time delay model is provided; section 3 defines some basic terminologies, where as section 4 gives a brief introduction of the SEIR (Susceptible–Exposed–Infectious–Recovered) model with temporary immunity period. Equilibrium points and threshold number of the system is discussed in section 5. In section 6, we discuss the analysis of the stability of the system. Later on some numerical simulations are carried out to illustrate possible behaviour of solution for different values of the delays in section 7. The paper finally ends with conclusion in section 8.

2. Related work

The model of worm propagation helps us to acknowledge the characteristics of worms and predict the trend of worm propagation. When epidemics spread, there are different forms of delay, which include immunity period delays, infectious period delay, incubation period delay etc. Hethcote et al. [4] proposed a model where the delay is introduced in the removed class to account for the period of temporary immunity. Kyrychko and Blyuss derived a time delayed SIR model with a general incidence rate and temporary immunity period [5]. Xue and Duan[6] developed an SIR epidemic model with nonlinear incidence rate and double delays due to the force of infection and temporary immunity period. Gao et al. [7] considered the delayed SEIR epidemic model with latent period delay. Zhang and Yang proposed a delayed SEIRS worm model with temporary immunity period in computer network [8]. Kim et al. [9] have considered some simple models and put some modification, like, in the simple SIR model once a node is cured after infection it becomes permanently immune, but Kim et al. allows this immunity to be temporary, since the cured nodes may again become infected, may be with a different strain of the same worm. Yao et al. [10] have proposed internet worm propagation model with time delay in quarantine. Dong et al. [11] developed a new computer virus model with time delay for SEIR model. They regard time delay as bifurcating parameter to study the dynamical behaviours which include local asymptotical stability and local Hopf bifurcation. Ren et al. [12] proposed a computer-virus-propagation model with varying latency period. Yang et al. proposed a generic epidemic model SLBS (susceptible-latent internal computers-infected computers breaking out-susceptible) of viruses, which is intended to establish a series of rational epidemic models of computer viruses [13].

3. Basic terminologies

3.1. Susceptible class

Represents the number of motes which are susceptible to the malicious signals in the wireless sensor network, that is, they are not yet infected at any time t.

3.2. Exposed class

Represents the number of exposed motes that are asymptomatic latently infected motes in the wireless sensor network which have been attacked by malicious signals but are yet to show any infective effects on the remaining section of the WSN.

3.3. Infectious class

Represents the number of infected motes which are infectious and are capable of spreading the malicious signals to other susceptible motes through contact.

3.4. Recovered class

Represents the number of motes which are ceased to be infectious and have acquired immunity, which may be permanent or temporary based on whether they remain in this class forever or they move back to the susceptible class and hence they stop being infectious to other motes.

4. Delayed epidemic model formulation

Our model is based on traditional SEIR model which has four states: Susceptible, Exposed (Infected but not yet infectious), Infectious and Recovered. Our assumptions on the dynamical model are as follows:

(a) The total population of motes is divided into four groups: Susceptible, Exposed (Infected but not yet infectious), Infectious and Recovered motes. Let $S(t)$, $E(t)$, $I(t)$ and $R(t)$ denote the numbers of Susceptible, Exposed, Infectious and Recovered motes respectively at any time t.